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Third-generation biodegradable plastics – A complementary strategy to tackle the marine litter problem

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ABSTRACT

The amount of plastic produced worldwide has reached 400 million metric tonnes in 2022. Estimated 3–5% of this amount ends up in the environment, where it poses significant threats to ecosystems and biodiversity. Littering, a growing global challenge, requires a combination approach to tackle its causes and mitigate its impact. There are different strategies to combat littering. Plastic waste is a complex subject needing a combination approach to deal with the current littering problem by supporting adequate waste infrastructures especially in developing countries. Consumer behavior and awareness must also be addressed. But even with immediate and concerted action to reduce consumption, more than 700 million tonnes of plastic waste will cumulatively enter the aquatic and terrestrial ecosystems until 2040. Waste management systems, even if improved, do not have sufficient capacity at the global level to cope with the huge mass of plastics entering the environment. Especially for plastic, which will foreseeable and inevitably enter the environment, where it can persist for hundreds of years ('forever' plastics), a solution is needed. Biodegradable plastics, that meet the criteria of 'Safe and Sustainable by Design' (SSbD), offer innovation perspectives and can be a complementary strategy to tackle the marine litter problem. 'Safe and Sustainable by Design' is a holistic framework for developing chemicals, materials, and products that prioritizes safety and sustainability at every stage of their lifecycle. The approach aims to create innovations that are inherently safe for human health and the environment while promoting long-term ecological, economic, and social sustainability.

In our view, biodegradable plastics should be used especially for products that are designed to enter the environment (marine or soil) or are inherently difficult to prevent from doing so. The following plastics should therefore - as a first step - be addressed in innovation efforts to become biodegradable:

1. All microplastics that may continue to be used in consumer products such as cleaning agents, scouring salts or cosmetics and care products (e.g. toothpaste) (in the EU already addressed by Commission Regulation (EU) 2023/2055 (European Commission, 2023a), see Section 3.4.3),
2. All microplastics that are used in paints, varnishes, coatings and sealants for the construction sector and are subject to intensive weathering,

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3. Rubber articles that are released into the environment as microplastics to a relevant extent during use,
4. Other plastic articles or fabrics that are subject to intensive abrasion during the use phase (cleaning cloths, sponges, drying cloths, cleaning rags, etc.),
5. Agricultural plastic products such as seed and fertilizer wrappings, thin mulch films, plant seedings, tree shelter tubes that are not removed from the soil (SAPEA – Science Advice for Policy by European Academies, 2020) (in the European Union already addressed by Regulation (EU) 2019/1009, (2019) and Commission Regulation (EU) 2023/2055 (European Commission, 2023a),
6. Fishing nets (especially trawls) and other plastic products for fishing/angling (De Domenico et al., 2023),
7. Textiles for intensive use in water (such as mats, splash guards, swimsuits, etc.)
8. Small plastic parts such as firework casings (SAPEA – Science Advice for Policy by European Academies, 2020),
9. Selected volume-relevant food packaging (Cowger et al., 2024),
10. Other disposable articles (e.g. cigarette butts (Araújo and Costa, 2019).

In view of the difficult political situation regarding the negotiations of a Global Plastics Treaty with upper limits for plastic production (European Commission, 2024), we believe there should be more discussion on whether all packaging that is particularly relevant for littering should also be degradable in the distant future.

1. Plastics and the (marine) environment

The amount of plastic produced worldwide has risen sharply over the past 70 years – to around 400 million tonnes (Mt) in 2022 (Statista, 2024). There are different studies on plastics leakage into the environment. “Given that the quantification of plastic leakage is a relatively new field, studies differ in their scope, methodology and assumptions. This plurality of methods has the benefit of providing a more complete overview of the plastics issue, with each study drawing to a different aspect of the problem. However, it also means that results of earlier studies diverge and are difficult to compare” (OECD, 2022a, p. 48). For to include leakage estimations in the Global Plastics Outlook database by the OECD (Organization for Economic Cooperation and Development) and to ensure the results of existing methodologies are more comparable, the OECD collaborated with three research groups. Fig. 1 shows the leakage from mismanaged waste and litter together with the upper and lower bound estimations prepared for the Global Plastics Outlook. The estimates for 2019 are 19 million tonnes (Mt) plastic leakage to both aquatic and terrestrial environments (range: 13–25 Mt), of them 6 Mt leakage to aquatic environments (range: 4–9 Mt). This is less than estimated for aquatic loss e.g. by Lau et al. (2020) (22–39 Mt/a), Borrelle et al. (2020) (19–23 Mt/a) or the IISD – International Institute for Sustainable Development (2022) (8–12 Mt/a). Regarding the estimations prepared for the Global Plastics Outlook, the authors conclude: “However, the lack of empirical data to validate the modelling means that these estimations are still uncertain (OECD, 2022a, p. 48)."

The experts agree on one thing: if no massive countermeasures are taken, the amount of plastic entering the environment will continue to rise. Even in an ambitious scenario, experts expect “between 20 and 53 Mt/year of plastic emissions to aquatic ecosystems by 2030, remaining at or exceeding 2016 levels despite tremendous reduction efforts by the global community” (Borrelle et al., 2020).

Depending on the type of polymer, the included compounds and their shape, plastic products are either lighter or heavier than water. Once discharged, a smaller part of the items sinks to the seabed, e.g. polyvinylchloride (PVC). The larger proportion floats on or under the surface of the water (packaging made of polyethylene (PE) or polypropylene (PP), for example). In the oceans, plastic waste currently circulates in five large gyres. The largest gyre in the Pacific is the size of Europe. Marine litter also accumulates in coastal areas, whether on the seabed or on the beaches on land. “For example, single-use plastics represent 50% of all European beach litter

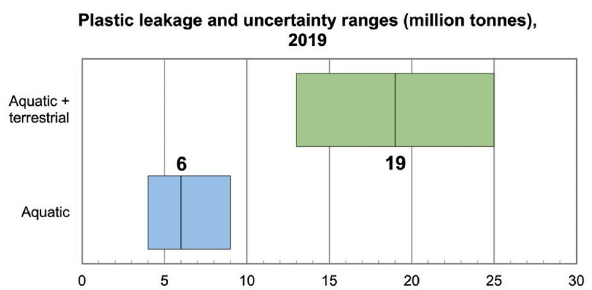

Fig. 1. The figure shows the leakage from mismanaged waste and litter together with the upper and lower bound estimations prepared for the Global Plastics Outlook. The estimates for 2019 are 19 million tonnes plastic leakage to both aquatic and terrestrial environments with a range of 13 to 25 million tons, of them 6 million tonnes leakage to aquatic environments with a range of 4 to 9 million tonnes

items by count" (European Commission, 2020d).

According to the United Nations Environmental Programme (UNEP, 2009) and the Global Plastic Outlook from the OECD (2022a), the majority of waste in the seas and oceans comes from activities on land (see Fig. 1). The main causes here are, on the one hand, the lack of an organized waste management system (around 2 billion people are not connected to an organized waste management system) and, on the other hand, careless handling of plastic products after use (littering). The plastic products are carried by rain, snowmelt and wind into the sewage system or directly into nearby watercourses and thus end up in the oceans with a time delay. Therefore, the solution strategies that we will discuss below must take into account that we have this enormous stock of plastic products in the waters, which only gradually reaches the sea after many years.

Plastic littering will increase, even in the best of all scenarios analyzed by experts (Lau et al., 2020). The authors come to the conclusion that even with immediate and concerted action, more than 700 million metric tonnes of plastic waste will cumulatively enter aquatic and terrestrial ecosystems.

Marine plastic pollution creates various adverse effects on the environment, economy and society. Sea life confuses macro- and microplastics with food (Machovsky-Capuska et al., 2019). Organisms entangle themselves, ingest the plastic, starve or suffocate (Gall and Thompson, 2015; Thushari and Senevirathna, 2020). But they also suffer from toxicological effects – plastics emit the additives mentioned above such as plasticizers (Oehlmann et al., 2009) or flame retardants, antibiotics, herbicides, and they can furthermore accumulate harmful compounds such as POPs or trace metals. Ingestion can be lethal or affect reproduction, growth or cause mutations (Teuten et al., 2009). Furthermore, plastic can travel comparably great distances in water and thus bears the risk of transporting invasive species or pathogens. Tourism, fisheries and human well-being are consequently greatly affected by marine litter.

All these figures and estimates relate to macroplastics, i.e. larger, solid plastic items such as films, packaging and other plastic products. Not included are microplastics; these are small plastic particles with a size below 5 mm (details see Section 3.1.1). Over the years, plastics become brittle in the marine environment, e.g. because of dissolution of additives such as plasticizers, or by UV radiation. In combination with the movement of the waves, plastics are then broken down into smaller and smaller pieces. In the end, they become 'microplastics'. These very small plastic particles, stemming from materials or fibers (from textiles) or intentionally added to products, are found in significant quantities in the environment (details see Section 3.1.2). These emissions can never be recovered, they are irreversible.

We still don't fully know what the consequences of these emissions will be (Kvale et al., 2021). But if we are not stopping the emissions, we are allowing them to continue. Therefore, the global community has set out to negotiate a binding agreement to counteract this (United Nations, 2022).

Are degradable plastics a solution to littering? And if so, what principles would a new generation of biodegradable plastics needs to follow to address the common concerns? We will examine these questions in this paper providing a roadmap for safe and sustainable biodegradable plastics.

2. Strategies to tackle 'littering'

Under the 2030 Agenda for Sustainable Development, the Sustainable Development Goal (SDG) 14 – 'Conserve and sustainably use the oceans, seas and marine resources for sustainable development' – is directly linked to the reduction of marine litter by its target 14.1: 'By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution'. In fact, there are several further SDGs with interfaces to marine litter and microplastics (UNEP,

Fig. 2. The figure shows the number and type of technologies directed toward collection and the type of plastic targeted, either macroplastics, microplastics, or both. There are 35 collection technologies, of them 28 for macroplastics, three for microplastics and four for both. There are 14 prevention technologies, eight for macroplastics and six for microplastics.

2022; Fig. 3).

Because of the great importance of the problems caused by the growing amounts of plastic products for the environment – under them marine litter (macroplastics) and microplastics – the United Nations initiated the development of an international legally binding instrument on plastic pollution, commonly known as the 'Global Plastics Treaty' (United Nations, 2022; UNEP, 2023b). They requested the Executive Director to continue to support and advance the work of the multi-stakeholder Global Partnership on Plastic Pollution and Marine Litter (GMPL). One of GPML's objective is to prevent and reduce losses of plastics through improved design, application of the 3Rs principle (reduction, reuse, recycling), by promotion of closed-loop systems and more circular production cycles and by minimizing waste generation throughout the life cycle of plastics (GMPL - Global Partnership on Plastic Pollution and Marine Litter, 2012).

In the following, we shortly review the different strategies to tackle marine litter and propose a complementary strategy, based on the 'Safe and Sustainable by Design' approach (European Commission, 2022a).

2.1. *Strategy 1: Waste management – circular economy*

In environmental policy discussions at European and global level, waste management is seen as a key strategy for solving the littering problem. This position has been advocated for years. In 2015, for example, the United Nations published a list of sustainable development goals, emphasizing the need for improved waste management (United Nations, 2015). This position is correct and should not be criticized. And in an ideal world, this solution strategy would also work. Waste would be collected worldwide by well-equipped collection services and taken to recycling and disposal facilities where the hierarchy of waste management is the top priority. Unfortunately, this is not always the case in practice.

Regarding the EU, which likes to see itself as a pioneer in environmental protection, total per capita waste generation decreased by 4.2% between 2010 and 2020 (EEA – European Environment Agency, 2023), and landfilling has been reduced. But in 2021, 24% of municipal waste had been landfilled still. Between 2010 and 2021, nearly all countries (except for Germany that landfills very small quantities of waste) reduced their reliance on landfill after all, with most significant reductions achieved by Lithuania (−71%), Slovenia (−51%), Estonia (−46%), Bulgaria and Finland (−45% both). However, nine of the 27 member states with in sum around 105 million inhabitants – which is just under a quarter of the EU population – still had landfill rates for municipal waste of more than 50% in 2021 (Malta: 85%, Greece: 78%, Romania: 76%, Cyprus: 62%, Croatia: 58%, Portugal: 53%, Latvia: 52%, Spain: 52%, Hungary: 51%) (EEA – European Environment Agency, 2024).

A third of the world's population does not even have an organized waste collection system. Not to mention the existence of recycling and disposal facilities. Over half of the world's marine litter comes from these developing countries or emerging economies such as China, India, Brazil. In particular, it is disposable one-way-packaging (packaging that is not reused) and disposable products

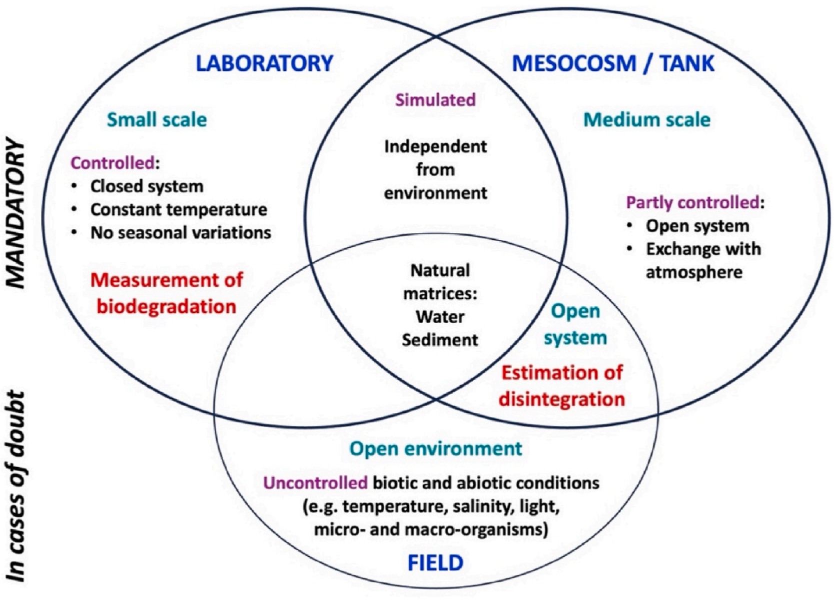

Fig. 3. The figure shows the tests for investigating biodegradability and disintegration of plastic. It consists of three overlapping circles: laboratory, mecocosm/tank and field. The laboratory tests include small scale tests to measure biodegradability under controlled conditions. The mecocosm/tank tests include medium scale tests with partly controlled conditions. The intersection of both circles are simulation tests, on the one hand independent of the environment, on the other hand with natural matrices such as water and sediment. The tests with natural matrices also represent an intersection of mecocosm/tank tests and field tests, the third circle. The tests to estimate the disintegration of plastics in natural media are carried out either by means of mecocosm/tank tests in open systems or in field tests - the third circle - in the open environment under uncontrolled conditions. Laboratory and mecocosm/tank tests are mandatory, field tests are used in cases of doubt.

made from these same 'forever' plastics that make up the largest share of this litter. The industrialized countries have exported their 'product culture' and profited economically from it without taking responsibility for this waste. From a legal perspective, it is particularly important here to view producer responsibility in the causal chain as comprehensively as possible, even if this would be a new (but not absurd) approach for marine pollution (Treaty on the Functioning of the European Union, Art. 191, 1: Union policy on the environment shall contribute to pursuit of the following objectives: preserving, protecting and improving the quality of the environment, …, promoting measures at international level to deal with regional or worldwide environmental problems, …) (For plastic producers' EPR see Section 2.4.).

Within the last 30 years, the situation has barely improved and, in our opinion, there is no fundamental improvement in sight for the coming years. The bare figures show that emissions into the sea have not decreased, rather the opposite. Waste management is unable to cope with the huge volumes of discarded plastic. Plastics production and – as public littering is widespread – subsequent pollution will increase, foreseeably in those regions of the world, where the infrastructures are least able to cope (SAPEA – Science Advice for Policy by European Academies, 2020). According to the UN's latest Waste Management Outlook (UNEP, 2024, Fig. 14), the share of municipal solid waste (MSW) going to uncontrolled disposal is 87% in Sub-Saharan Africa, 79% in Central and South Asia and 36% in East and South-East Asia. In a 'waste as usual' scenario, the volume of uncontrolled disposed MSW will almost double from 810 million tonnes in 2020 to around 1570 million tonnes by 2050 (UNEP, 2024, Fig. 17).

Against this background, too, improvements in waste management are being discussed internationally, for example at UN level as part of the aforementioned Global Plastics Treaty (United Nations, 2022). This topic is at the forefront there and the financing of better waste management is also part of the negotiations. However, judging by the negotiations of the Intergovernmental Negotiating Committee so far, it is unclear whether the international community will agree on a convincing solution. This remains open, especially after the failure of the negotiations at the end of 2024.

An improvement in waste management can be achieved perhaps in the long run, but it is unclear to what extent. In an optimistic scenario, the OECD assumes it is possible to reduce littering rates by over 90% by 2040 with a moderate reduction in plastic consumption and a massive global expansion of waste management (OECD, 2023). The World Wildlife Fund (WWF) and the German Alfred Wegner Institute have also published a very optimistic scenario (Tekman et al., 2022). According to this, the littering rate could be reduced by 36–91% by 2050 through "a massive reduction in sources, improved waste management, recycling and disposal on a global scale". However, all optimistic scenarios only succeed in slowing down the increase in emissions (Tekman et al., 2022).

Experts warn that increased waste management capacity alone cannot keep pace with projected growth in plastic waste generation. They call for a "fundamental transformation of the plastic economy to a circular framework" (Borrelle et al., 2020).

The circular economy is positioned as a supplement or improvement to waste management. Based on the model of the Ellen MacArthur Foundation (2015), circular economy means that, under others, new products and assets are designed and produced in a way that virgin material consumption and waste generation is reduced and resource and material loops are closed by recycling of end-of-life products and materials (EIB – European Investment Bank, 2023).

Circular economy for plastics means: New plastics are to be created from old plastics. In Europe, for example, in December 2018, the European Commission launched the 'Circular Plastics Alliance' initiative under the European Strategy for Plastics (European Commission, 2018), "in particular under Annex III related to voluntary pledges by industry" (European Commission, 2020c). Companies which sign the 'Declaration of the Circular Plastics Alliance' thereby commit themselves to "take action to boost the EU market for recycled plastics up to 10 million tonnes by 2025" (European Commission, 2020c).

The hope is that material recycling in particular can reduce the demand for raw materials for new materials (virgin plastics) and thus solve the problems of the plastics sector. The 'circular economy' concept or narrative has been developed for this purpose. Closing the loop is a high, but difficult to achieve goal. Chemical and physical concerns are formulated at this point. What about the inevitable losses, efficiencies etc. in recycling? Scientists point out that closed-loop recycling is not possible for today's real products, except downcycling for very few cycles (Huether et al., 2022). "The basic laws of nature tell us there will be neither a zero-waste society nor a 100% circular economy. Approaches to circular economy should be assessed according to their contribution to resource conservation, the energy required, waste generated in present and future, and their social and economic impacts" (Friege and Kümmerer, 2022).

However, the narrative can be saved as an 'almost' closed cycle and with an even more radical strategy: in a circular economy, the product (the workpiece) should then be designed in such a way that it can preferably be repaired, reused, then refurbished and reprocessed and finally, if only little value remains, recycled at the very end. The extraction of new materials and leakages are minimized to almost zero, or so it seems.

Following the Ellen McArthur Foundation, a circular economy has the potential by 2040 to reduce the annual volume of plastics entering our oceans by 80% und reduce greenhouse gas emissions by 25% (Ellen MacArthur Foundation, 2024). The strategy to reach these goals includes the elimination of all problematic and unnecessary plastic items, the development of reusable, recyclable, or compostable plastics for areas of application where plastics are indispensable, and the circulation of all the plastic items in use in the technosphere.

Europe belongs probably to the most developed regions in the world in terms of the circular economy. However, there is a lot of rhetoric involved here. China, on the other hand, has ambitious plans for a circular economy, too, and manages remarkable achievements (Bleischwitz et al., 2022). A circular economy would mean replacing virgin plastic with recyclates. We have analyzed the current situation in the EU and Germany in more detail and found that the real recycling rates of plastics are very meagre (Lahl et al., 2024a).

In summary, both waste management and the circular economy are suitable strategies for reducing the problem. However, the successes to date are marginal and therefore need to be improved (Bleischwitz, 2022). Against this background, further strategies are needed to tackle the littering problem.

2.2. Strategy 2: Plastics removal from the environment by technologies (PRTs)

Currently, a variety of clean-up technologies for removing plastic waste from oceans, rivers and coastal areas are available, see Fig. 2. All of these technologies discussed here are limited in their effectiveness, and they do not tackle the problem at source. It is therefore not surprising that there are also concerns from the scientific community as to whether this solution strategy is ecologically favorable at all (Falk-Andersson et al., 2023; Bergmann et al., 2023). Studies even show that the projected impact of both single and multiple clean up devices is very modest (Hohn et al., 2020). So, experts do not reject this way of cleaning the oceans in principle due to a lack of alternatives. However, they point out the risks that fishing for plastic waste can also lead to marine organisms being fished out and other collateral damage. The collected waste is so diverse and thus hard to sort, recycle or incinerate. They therefore argue in favor of careful practice and the establishment of legal rules ("cleaning up without messing up" (Falk-Andersson et al., 2023).

PRT rank low on the zero-waste hierarchy and are only accepted on a transitional basis as a tool to reduce existing plastics in pollution hotspots. "Ideally, these will be interim measures while plastic production, as the source of pollution, is significantly phased down" (Bergmann et al., 2023).

Non-Governmental Organizations (NGOs) take a similar view (Eia Environmental Investigation Agency, 2023). And in view of the negotiations on a Global Plastics Treaty, there are fears that such secondary solution strategies could prevent primary upstream solutions. The authors of Fig. 2 demand that PRT "should be used in tandem with other preventative solutions, such as sustainable, biodegradable material to replace plastic or improved waste management systems" (Schmaltz et al., 2020, pp. 11,13). In sum, such an approach should be combined with solutions upstream and in line with all relevant circular economy proponents. PRT is an add-on and can supplement, but not substitute other strategies.

2.3. Strategy 3: Emission prevention or reduction

There are several technical options to prevent or reduce at least the emission of microplastics into the environment. E.g., for municipal wastewater treatment plants, an additional treatment step for removal of micropollutants and microplastics would be an excellent solution. Within sewage sludge incineration, microplastics would be mineralized and even serve as energy source. But currently, direct sewage sludge reuse in agriculture is permitted e.g. in all EU Member States if it complies with national regulations (Council Directive 86/278/EEC, 1986). In recent years, only three of the EU Member States that provided data have incinerated sewage sludge to a greater extent (at least 75%): Netherlands, Belgium and Germany (EUROSTAT, 2024). The incineration of sewage sludge from municipal wastewater treatment is likely to increase in the coming years, as this material contains high levels of phosphorus. As phosphate rock and phosphorus are critical raw materials in the EU (Regulation (EU) 2024/1252, 2024), the European Commission wants to accelerate phosphorus recovery from sewage sludge (European Commission, 2022c). The highest yields can currently be achieved from sewage sludge ash (Serrano-Gomez et al., 2023). In many emerging and developing countries, large parts of the population are not connected to a functioning wastewater disposal system. And a third (P precipitation) and fourth (microplastic removal) treatment stage is likely to be the exception rather than the rule, as is the incineration of sewage sludge. E.g., even in 2022, there were almost 30 countries in which 80 % or more of the population as a whole or in urban or rural areas had no access to safely managed sanitation services (SDG indicator 6.2.1) (United Nations, 2023). Therefore, it can be considered an 'end-of-the-pipe' solution with high additional efforts, and other strategies are required here.

Road runoff should be collected and cleaned (e.g. by sedimentation tanks or filters) before it is allowed to enter the tap water. Tire abrasion should be limited. With the new Euro 7 emissions standard (from the end of 2026), non-exhaust particles from tire wear ("non-exhaust particle emissions") will also be limited (in addition to brake wear) (Silvestro, 2022). However, the test procedure and limit values have yet to be defined within UN Regulation No. 117 by the United Nations Economic Commission for Europe (UNECE) (Lewis, 2024; UNECE, 2016).

Concerning losses from the production and processing of plastic pellets, industry has launched the Operation Clean Sweep® (OCS) in 2015. "OCS is an international programme designed to prevent the loss of plastic granules (pellets, flakes and powders) during handling by the various entities in the plastics value chain and their release into the environment" (Operation Clean Sweep®, 2021). The last published annual report is for 2019, according to which signatory companies have implemented the six OCS commitments to varying degrees: in 2019, 97% of companies had analyzed sources of (potential) pellet spills at their facility, 88% performed periodic inspection of their facility to verify the performance regarding OCS, but at 39% OCS is not part of a periodic training programme (Plastics Europe, 2020, p. 19).

One source of emissions that has only recently come into focus are plants in which plastics are processed for recycling (e.g., shredding and washing) (Lahl and Zeschmar-Lahl, 2024b): "For example, a measurement campaign at a recycling plant for mixed plastic waste in the UK showed that around 6% of the plastic waste (4–130 kg/t) was discharged as microplastics with the wastewater (Brown, A., et al., 2023). The plant had a high separation efficiency for particles with a size above 40 μm (μm), with the majority of particles with a size of 5–40 μm being separated. Particles with a size <5 μm were generally not removed by the filtration and ended up in the wastewater. From their data, the authors concluded that without wastewater filtration, 13% of the plastic throughput would end up in the wastewater. The authors of the study from the UK cite two comparable publications, one on Polyethylene terephthalate (PET) bottles (Guo et al., 2022) and one on different types of plastic waste (electronic plastic waste, PET bottle waste, and household plastic waste) (Suzuki et al., 2022), and conclude that – taking into account the different analytical methods used to determine the concentrations of microparticles in the process and wastewater of the recycling plants – the results of all three available studies are coherent" (Brown, A., et al., 2023).

In a recent study published in may 2024, microplastics (MP) in the wastewaters of four plastic recycling facilities (PRF) located in

Türkiye were characterized. The authors estimate the discharged amounts of microplastics can reach 4.6 kg MP/ton of plastic recycled. With regard to the PRFs capacity, discharged MPs exceed possibly 30,000 tons (Çolakoğlu and Uyanık 2024).

The database for this is currently very small, but there is no doubt that mechanical processing like shredding and washing of plastic ad plastic waste leads to the production and emission of microplastics. Appropriate requirements for wastewater treatment must be specified by law, especially in the case of direct discharge into water bodies, but also for indirect dischargers, so as not to overstrain the treatment capacity of municipal wastewater treatment plants.

Washing of textiles made from synthetic fibers is another relevant source for microplastics emissions. It is possible to minimize these emissions by technical means. E.g., for washing machines, the use of laundry balls or the installation of a filter should become mandatory, as will be in France for new commercial and domestic washing machines from 1 January 2025 (European Commission, 2023b).

2.4. Strategy 4: Extended Producer Responsibility (EPR)

According to a publication from April 2024, data from a 5-year (2018–2022) worldwide (84 countries) programme to identify brands found on plastic items in the environment through 1576 audit events showed 56 companies accounted for more than 50% of the items found. The top five brands globally account for 24% of the total branded count. Number one is The Coca-Cola Company (11%), followed by PepsiCo (5%), Nestlé (3%), Danone (3%), and Altria (2%) (Cowger et al., 2024).

The producers of fast-moving consumer goods like packaging for food and drinks of course, should be held accountable, regarding of Extended Producer Responsibility. EPR makes producers responsible for their products at the post-consumer stage of the lifecycle, e.g. electronics, packaging, vehicles, and tires. It is widely adopted by governments and companies across the OECD members and beyond. Following the OECD, “EPR has the potential to provide producers with incentives for the design of more easily recyclable or re-useable products” (Brown, A., et al., 2023, p. 8).

In many developed countries EPR schemes are accepted (see Dri et al., 2018; GAP for EPR, 2024). E.g., the separate collection of lightweight packaging started in Germany in 1990, where the Duales System Deutschland GmbH (DSD GmbH) was founded by trade and industry in order to fulfil their legal obligation towards packaging waste. Following the implementation of the EU Packaging and Packaging Waste Directive (Directive 94/62/EC, 1994Directive 94/62/EC, 1994), the EPR-based model has since then until 2014 been followed with some degree of variation in the 27 EU Member States, plus United Kingdom, Türkiye, Serbia, Norway, Iceland, Ukraine and four provinces of Canada (Cimpan et al., 2015, cited by Zeschmar-Lahl et al., 2016). In the EU, EPR will be expanded on disposable beverage bottles by the single-use plastics directive (Directive (EU) 2019/904, 2019). But especially in developing and least developed countries, the introduction of EPR schemes has to face bigger problems, like e.g. government capacity, transparency or the involvement of the informal waste sector (OECD, 2024a). “As well, in developing countries exhibiting a developing tax base, collection or administration, EPR may present an attractive solution for financing waste management” (Brown, A., et al., 2023, p. 53,54).

However, the successes of EPR in industrialized countries are also limited, but there is room for improvement. Sanctions are key if targets are not achieved. It is important that in these cases, not all EPR participants, but only the responsible actors are sanctioned individually. But this is rather rare in the established systems. EPR should be a starting point to convince leading polluter brands to switch to biodegradable plastics.

2.5. Strategy 5: Education, consumer behavior and awareness raising

Another solution strategy is based on the self-image of many representatives of the plastics industry, who see littering as a social problem. Here is a quote from the early 1970s that encapsulates this thinking very well: “We see this as a social problem. There is nothing we can do about it – we only make the stuff. … It is up to the public to learn to be more responsible about throwing it away” (Anon, 2019; cited by Hees, 2019, p. 110).

Awareness raising and education thus become the task of a pedagogical solution strategy. Irrespective of the question of the responsibility of the plastics industry, this solution strategy is not wrong either. It has also been implemented quite successfully in the education system and in the media in recent decades. It can also be considered necessary part of socio-cultural changes in consumer behavior, in particular when food packaging and single-use plastics are to be addressed. Perceived consumer effectiveness and personal responsibility could become critical variables in developing future policies on sustainable consumption (Kautish et al., 2021; van Oosterhout et al., 2023). But so far it has not made significant progress in reducing littering. To put it in a nutshell: An educational solution strategy will not reach those who are in a daily struggle for survival, food and security. So, here too, we recommend not focusing exclusively on the education strategy. We would also like to emphasize the great impact that was achieved with projects and programs in line with this strategy in terms of agenda setting (e.g. ban for plastic bags), capacity development for the UN Ocean Decade (Zhang et al., 2024) and an enlightened society.

2.6. Strategy 6: Tackling the causes

2.6.1. Sufficiency – reduction of plastic production and use

Up to now, the discourse on the sustainability of our societies has largely ignored the need for sufficiency (SRU, 2024a). The German strategy for a circular economy (BMUV, 2024) proposes a target of halving resource consumption to 8 tonnes (Megagram, Mg) per capita per year by the year 2045.

The growth in plastic production and use has to be halted. This is why the first of the possible core obligations of the proposed UN

Plastic Treaty is “phasing out and/or reducing the supply of, demand for and use of primary plastic polymers. … Reduced use of primary plastic polymers and increased use of recycled material would see a greater flow of plastic being cycled back into the economy as ‘secondary plastics’, and would result in smaller inflows of new ‘virgin’ plastic and fewer outflows into final disposal (with zero plastic leaking into the environment)" (UNEP, 2023a).

The plastics industry, on the other hand, warns against such measures, as developing nations, “especially those reliant on critical products that serve public needs at affordable prices, could be particularly affected by such measures, leading to repercussions on SDG 2, SDG 3 and SDG 6" (Plastics Europe, 2023) (SDG 2: zero hunger, SDG 3: good health and well-being, SDG 6: clean water and sanitation). And it points out: “Approaches to production caps need to be carefully balanced with the accessibility and affordability of alternatives and the unique circumstances of different countries."

But these careful ‘words of warning’ do not match with industry’s plans. According to the Global Plastics Outlook (2022), global plastics use is projected to triple between 2019 and 2060, from 460 million tonnes (Mt) to 1321 Mt, mainly driven by economic growth (OECD, 2022b), mainly in the emerging countries. Scientists are therefore calling for the production of virgin plastic to be phased out by 2040 in order to combat the effects of plastic on the environment, the climate and people (Bergmann et al., 2022).

In addition to the ecological necessity, the idea of sufficiency problematizes the unequal sharing of energy, resources and other environmental goods, too (SRU, 2024b, p. 66). It remains to be seen whether the proposed UN Plastics Treaty will really take effective measures against the further increase in the production and use of plastics.

2.6.2. Closed loop recycling of plastics

Borrelle et al. (2020) pointed out that – unless growth in plastic production and use is halted –, “a fundamental transformation of the plastic economy to a circular framework is essential, where end-of-life plastic products are valued rather than becoming waste”. The plastic industry itself relies on the transition to circular plastics production, including ‘Design for Circularity’, recycled content targets per industry sector and re-use targets for specific applications (Plastics Europe, 2023).

As pointed out above in Section 2.1, the approach of closed loop recycling is right and good, but must find a solution to the problem of the diversity of polymers and additives, especially hazardous ones, in plastics. E.g., “the complexity of plastic polymers and even more so of additives has increased enormously in recent years. This makes the high-quality recycling of mixed plastic waste considerably more difficult. Some additives have now been strictly regulated or even completely banned for good reasons (‘legacy additives’). Material or mechanical recycling generally utilizes old plastics that still contain these substances. Consequently, products that are manufactured using such recyclates are contaminated with these harmful substances” (Lahl and Zeschmar-Lahl, 2024a, 2024c). The use of such recyclates for contact-sensitive products is currently under discussion (Lahl and Zeschmar-Lahl, 2024a, 2024c).

2.7.

Strategy 7: Replacing ‘forever’ plastics with biodegradable alternatives

Under current market conditions, degradable and safe plastic products will undoubtedly be more expensive than today’s ‘forever’ plastic products. Therefore, shaping markets with mission-oriented policies and binding regulation will be pivotal. The starting point for substitution could be plastic products intentionally released into the environment, where a ban is no option.

In 2022, the European Commission has published a Communication on biobased, biodegradable and compostable plastics. This is intended to promote bio-based and biodegradable plastics under clearly defined conditions (European Commission, 2022b): ‘Many new plastic materials are emerging on the market. Biobased, biodegradable and compostable plastics can bring advantages over conventional ones if designed for circularity, produced safely and from sustainably sourced feedstock, prioritizing the efficient use of secondary biomass, and compliant with relevant standards. … The aim of this policy framework is to bring clarity and understanding of these plastics and to guide future policy developments at EU level such as under eco-design requirements for sustainable products … ’

And with the regulations on fertilizers (Regulation (EU) 2019/1009, 2019) and on banning ‘forever’ microplastics and opening up to degradable plastics (European Commission, 2023a), the Commission has taken a paramount step. It is appropriate to the scale of the problem that this regulation begins with plastic products that are released into the environment as intended and cannot be captured by waste management measures.

One of the possible core obligations of the proposed UN Plastic Treaty is “promoting the use of safe, sustainable alternatives and substitutes. … Encouraging the use of safe, sustainable substitutes and alternatives to traditional plastics, such as alternative materials and biodegradable or compostable materials, could reduce the health risks associated with plastic pollution and promote circularity in the plastics industry” (UNEP, 2023a, p. 10).

So, a solution strategy could comprise replacing ‘forever’ plastics with degradable plastics (substitution) for those plastic products which are mainly responsible for the littering problem. These are e.g. products which are for uses that unavoidably lead to release into the environment or wastewater (Schmaltz et al., 2020).

In the following, we will review the previous attempts for biodegradable plastics (Section 3) and propose a new (third) generation that is safely and sustainably designed (Section 4).

This substitution strategy would complement the other solution strategies and requires them as a prerequisite. This substitution strategy is compatible with the circular economy option because the degradability or compostability is integrated into the natural cycles, as is also desired for biowaste from households. The fight against littering needs to be based on several efforts, which would make it easier to achieve the objectives. This strategy would be fully in line with the European Commission’s Recommendation for the ‘Safe and Sustainable by Design’ (SSbD) framework, see Section 4.

3. Materials and methods

3.1. Macro- and microplastics

3.1.1. Definitions

Microplastics are defined as plastics smaller than 5 mm; anything larger is regarded as macroplastics. Microplastics are subdivided as follows:

- Primary microplastics ('microbeads') are produced industrially and are used for technical purposes (e.g. as abrasives) in products such as cosmetics (peelings, toothpaste) or cleaning agents (Cole et al., 2011).
- Secondary microplastics come from the fragmentation of macroplastics (e.g. abrasion of tires and markings on roads).

Within the marine environment, microplastics can be further degrade to 'nanoplastics', i.e. plastic particles or fibers with a size of less than 1 μm (<0.001 mm).

3.1.2. Microplastic emissions into the environment

In the EU, emissions of primary microplastics to the environment mainly occur via the wastewater pathway (ECHA – European Chemicals Agency, 2019a; 2019b). Wastewater treatment plants can retain 90–99% of microplastics, with the retained loads ending up mainly in sewage sludge, which is either incinerated or enters agriculture, where it is a major pathway into the soil.

The primary microplastics emissions to the environment in the EU are estimated at 10,000–60,000 tonnes per year (t/a). In addition, further primary emissions into the water path come from tire abrasion (94,000 t/a) and losses from the pre-production of plastic pellets (41,000 t/a), road markings (15,000 t/a) and clothing washing (13,000 t/a) (ECHA – European Chemicals Agency, 2019a, p. 10). Another source of microplastic emissions not yet included in the above figures are plastic recycling plants, according to the latest findings (Brown, E., et al., 2023; Çolakoğlu and Uyanık, 2024) (see Section 2.3).

3.2. Biodegradability of plastics (and compounds)

3.2.1. Degradation processes

Degradation processes for plastics can be divided into chemical, physical or biological degradation. For example, hydrolysis in an aqueous environment leads to the degradation of plastics through the incorporation of water molecules. Physically, degradation can be caused by light and atmospheric oxygen (photochemical oxidation). And purely mechanical decomposition of an end product by waves leads to the disintegration of a film or a cup. Finally, there is biodegradation by microorganisms (enzymes, to be precise). In the real environment, the different degradation processes will take place simultaneously. In the following, the degradation of plastics by microorganisms is considered because it corresponds to our definition of degradability (microbial degradation). Microbial degradation (aerobic) therefore means: Plastics must be converted to CO_2 and water (possibly mineral salts) and into microorganic biomass. Carbon is converted to biomass or CO_2, hydrogen to water, oxygen in the molecule becomes H_2O and CO_2.

3.2.2. Biodegradation of polymers

"For every organic substance produced by a living organism, there exists, somewhere in nature, an enzyme capable of breaking that substance down" (Commoner, 1971, p. 44). This is true for all natural occurring polymers, such as cellulose or chitin. Their deconstruction is accomplished in nature by "synergistic enzyme cocktails that evolved over millions of years" (Knott et al., 2020). Plastics have only been present in the environment on a large scale for a good 50 years. Nevertheless, some types of microorganisms have evolved the capacity (enzymes) to utilize synthetic polymers as carbon and energy sources – under optimum conditions (e.g. temperature, pH, contact time, concentration, particle size mainly <1 mm) (Bhandari et al., 2021; De Jesus and Alkendi, 2022).

Quantitatively important types of polymers are not or not significantly biodegradable in the environment. Polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyvinylchloride (PVC) are among the most persistent materials ever invented by mankind. The main reason for this is the polymer chain, which consists of carbon-carbon bonds, one of the strongest bonds we know of. The biodegradation time of pure carbon chain polymers such as PE or PP are extremely long (Bertling et al., 2022). As mentioned, these polymers are considered to be non-degradable. Experts state, that, overall, the microbial degradation processes known to date for conventional plastics are too inefficient. It is therefore not possible to speak of a real biodegradation of the materials (Kreutzbruck et al., 2021).

Other polymers such as PET, which have oxygen in the polymer or are formed via oxygen bridges, are – depending on the structure – not quite as stable. Once abstracted from the protective effect of admixed additives, the key to the degradability of the polymer is the bond in the molecule that the enzyme can attack. Entire functional groups such as hydroxyl, carbonyl, peptide or ester bonds, urea or carbamate bridges and amides improve biodegradability. The more points of attack there are in the polymer, the faster biodegradation takes place. This is the reason why plastics like PET are generally considered to be to a certain extent biodegradable, even if only slowly (Knott et al., 2020; van den Heuvel, 2022).

Another important point defining biodegradability is the length of the polymer chain. A long chain only can be degraded outside of the microorganism. Degradation turns long chains into shorter molecules. If the degradation fragments are of a size that allows them to enter the interior of the cells, further biodegradation is easier.

3.2.3. Biodegradation of plastics

The plastic products that end up in the environment are as a rule not pure polymers, but compounds made from at least one type of polymer and various additives. Many of the additives are used for shielding the polymer molecule or the plastic compound or one or more of the other additives against chemical (oxygen), physical (UV radiation) or biological 'attacks' (fungi, bacteria) (Schwarzenbach et al., 2021; Gugumus, 2021; Ochs, 2021). Depending on the application, the share of additives in a plastic compound can reach more than 50 weight-% (wt.%), e.g. in flexible PVC (European Commission, 2004). Against this background, the information on the biodegradability of pure polymers under optimized conditions (Section 3.2.2) should not be overestimated.

However, there exist further properties that define the speed of enzymatic degradability. The enzyme must be able to reach the surface of the plastic part. The degradability of a plastic product therefore also depends on the ratio of volume to surface size. Then there are plastics that are amorphous or have crystalline parts. The latter greatly hinders degradation because the polymer chains are very tightly packed and the enzymes have difficulty reaching the inner polymer chains. The enzyme must then fit chemically like a key into the lock of the plastic's point of attack. And the chemical environment is also important: higher temperature and biological activity promote degradation. For example, a biodegradable plastic, a Polylactide (PLA) film, was only slightly degradable at 20 °C (less than 10 %), but around 90 % at 60 °C (Kreutzbruch, 2021). And last but not least – as said before – the additive formulation is relevant. Without additives that 'intercept' the chemical attack on the polymer molecule, degradation is faster.

3.2.4. Biodegradation under environmental conditions

The biodegradation of a polymer or a plastic particle in the environment depends on several factors. For example, the microorganisms must be present in the environmental medium in sufficient quantities. On the high seas, e.g., the concentration of microorganisms in seawater is comparatively low.

Not every microorganism can break down every substance; they are specialized. Microorganisms need the right enzymes to break down the substance. In the competition between microorganisms, a supply of defined substances leads to the proliferation of organisms that contain enzymes that can break down the substance (competitive advantage through food intake).

Moreover, degradability in the laboratory test does not solve all technical questions. For example, there is a problem as to whether the degradability achieved in the laboratory in the standard tests is also sufficient in sewage treatment plants or the open environment. "As a common principle, a solution of the test material is inoculated with a low amount of microorganisms, in the presence of mineral nutrients, but in absence of any other carbon source than the test material itself… Biodegradation will indeed only be observed in case the inoculated micro-organisms are able to source energy and carbon solely from the test material – and this in a sufficiently efficient way, to allow the exponential microbial growth that is required to establish a self-accelerating degradation of the material" (Byrne et al., 2021).

3.3. Experiences with the degradability of biodegradable plastics

3.3.1. First-generation biodegradable plastics – a failure

The first generation of degradable plastics was primarily the result of political will in view of the emerging problems in the 1970s and 1980s. In view of the incipient plastic pollution, many parliaments and governments in the West demanded that plastics should be degradable. In the US, for example, this was primarily positioned as a solution to the landfill problem. In the UK, maritime pollution was already being addressed at this time. In the first environmental programme of the West German government in 1971 it was stated that, from the side of waste disposal, it is demanded that plastics should be easily biodegradable (Bundesregierung, 1971, p. 47).

Up to that point, the development of degradable plastics was based on the experience of polymer chemists at the time. Chemists were faced with the task of using chemical additives to make polymers more stable and resistant to ageing (chemical attacks). The task at the time was therefore to create longevity. The new task was to reverse the previous practice, i.e. to think about ways of destabilizing the polymer. E.g., British chemist Gerald Scott realized … 'the indestructible mass he was creating was a potential menace. He began wondering whether, having stabilized it, he could make it unstable again' (Anon, 2019, cited by Hees (2019), p. 98).

The persistence of 'forever' polymers is due to the fact that these polymers lack bonds in their backbone that can be readily cleaved through abiotic or enzymatic hydrolysis and oxidation (SAPEA – Science Advice for Policy by European Academies, 2020). Therefore, chemical oxidation with, for example, atmospheric oxygen often is the first crucial step in the degradation of these polymers. Photooxidative degradation is, in contrast to enzymatic degradation, also effective against polymers with a carbon-carbon chain. Energy-rich light rays (e.g. UV photons) excite molecules of atmospheric oxygen and generate highly reactive oxygen (as a radical or single oxygen). However, this process is very limited in water or soil in the absence of this radiation in particular. In addition, many plastic products are protected against such UV attacks by additives (stabilizers), see Sections 1 and 3.2.3.

In the first generation of degradable plastics, the idea was to replace the additives that prevent oxidation with additives that cause or enhance oxidation. Consequently, oxo-additives or co-polymers were mixed into the conventional 'forever' plastics, for example, to which atmospheric oxygen and UV rays can attack. Another variant was to mix the 'forever' polymers with biodegradable natural substances such as starch in order to stimulate biotic activity.

So, the biggest conceptual mistake was to stick with the polymers of 'forever' plastics. And then they were launched on the market too early and without sufficient validation through degradability tests. Nevertheless, these plastics were widely communicated as a solution to the problem. Subsequently it became apparent, which today seems almost trivial from a historical distance, that biodegradability did not work sufficiently. Although the plastic products disintegrated and aged more quickly, they were still recognizable years later as packaging, including e.g. the colored imprint, in landfill sites.

The fate of the first generation of biodegradable plastics is quickly recounted. There were disappointments, protests, calls for boycotts and – after being banned by the EU (Directive (EU) 2019/904, 2019, Article 5) – disappeared from the market. In January 2024, the General Court endorsed the prohibition on the placing on the market of oxo-degradable plastic (Court of Justice of the European Union, 2024): “According to the scientific studies available when the directive was adopted, the level of biodegradation of that plastic is low to non-existent in an open environment, in landfill or in the marine environment. In addition, plastic containing a pro-oxidant[3] additive is not suitable for any form of composting. Lastly, recycling such plastic is problematic since the technologies available do not allow reprocessors to identify plastic containing a pro-oxidant additive and to sort it from conventional plastic. (Footnote [3]: Since the parties use various terms for plastic to which a pro-oxidant additive has been added, the General Court has chosen to use the most neutral term possible, namely ‘plastic containing a pro-oxidant additive’.)"

It is not unusual for developments to fail in the first stage. However, these mistakes and the promise of a solution at the time have discredited the debate on the biodegradability of plastics to this day.

3.3.2. *Second-generation biodegradable plastics*

3.3.2.1. Shift towards natural polymers. For the second generation, the focus has shifted more towards natural polymers. This is because nature has developed its own resistant tailor-made products over millions of years – e.g. polymers that are persistent for years and decades in extreme cases and then decompose into harmless natural building blocks such as sugar. The typical polymers in nature are proteins, polysaccharides, lignin and natural rubber.

Turning to natural polymers was certainly the right step to achieve degradability in the first place. However, there are bio-polymers in nature that can also be very persistent. A good example of this is wood, which can last for decades or even centuries in water (see Venice). A great deal has therefore been invested in rapid degradability and the standardization of test systems for second generation plastics.

In the early 1990s, for example, the US agricultural companies Cargill and ConAgra went public with the news that they were working on the development of polylactides. Everyone knows the smell of sour milk. The reason: Lactic acid has been formed from sugar (glucose). As a monomer, lactic acid can form a polyester (polymer) of any chain length with other lactic acid molecules. After use, this polymer can be broken down again via lactic acid to CO_2 – a good example of the second generation of degradable plastics.

Degradable polymers commonly used today are the following:

- Polylactide (PLA) is a semi-crystalline thermoplastic, produced by polycondensation; monomer: lactic acid, produced by fermentation of sugar or starch.
- Polyhydroxybutyric acid (PHB) is one of the first biobased plastics to become widely known, part of a larger family of natural polyesters that are now known as polyhydroxyalkanoates (PHA); a number of bacteria (and algae) store energy and carbon in the form of PHA, which can be filtered out of the bacterial mass and converted into plastics.
- Polybutylene succinate (PBS) belongs to the group of linear aliphatic polyesters. It is synthesized by polycondensation of the two monomers succinic acid and 1,4-butanediol (currently on a fossil basis). It is readily biodegradable due to the structurally high oxygen content in the polymer molecule (SAPEA – Science Advice for Policy by European Academies, 2020).
- Polycaprolactone (PCL) is a polyester, mainly produced using fossil fuels today (Nair et al., 2017); it is readily biodegradable, the biological attack occurs here, too, at the ester site.
- Polybutyrate adipate terephthalate (PBAT) is produced from 1,4-butanediol, adipic acid and terephthalic acid (currently on a fossil basis), and is offered by BASF under the product name ecoflex (BASF SE, 2024).
- Polyisoprenes are a group of polymers consisting of linked isoprene units; monomers are produced by many plants and animals; their polymers are the main component of natural rubber.
- Starch is a homopolymer of linked glucose; polyglucose is an important storage compound found in plants.
- Cellulose is a homopolymer of linked glucose. It has a longer chain length than starch and is an important component of the plant cell wall.
- Lignin is a polymer consisting of phenylpropane units. The aromatic building blocks in lignin are linked via C–C bonds and ester bonds to form a complex and very stable macromolecule.
- Chitin is a homopolymer of linked units of acetylglucosamine. It is mainly found in the exoskeleton of insects and crustaceans as well as in the cell wall of fungi.

In nature, there are also polymers that are easily degradable because this is necessary for defined reasons, for example PHA, which is ‘deconstructed’ by bacteria for energy supply or nutrition in times of deficiency. This was a starting point for the development of the second generation of fast degradable plastics. Chemically, the degradable biopolymers or plastics differ from the ‘forever’ plastics in that they contain bonds in their backbones that are susceptible to hydrolytic or oxidative cleavage (e.g. double bonds, ester groups, alcohol groups, amines).

Global production of bio-based plastics (biodegradable + non-biodegradable) reached 1.9 million tonnes in 2022, – this is roughly 0.5% of the over 400 million tonnes of all plastic produced per year. Of the 1.9 million tonnes plastics, only 28% were biodegradable. For the EU plus three non-EU countries (United Kingdom, Norway, Switzerland), the annual production in 2022 was 0.4 million tonnes, of which 35% were biodegradable (Plastics Europe, 2024).

3.3.2.2. Biodegradability data for second-generation plastics. As part of a joint research project (IKK – Institut für Kunststoff- und Kreislauftechnik, 2024; MaBiKu, 2024) led by the Institute of Plastics and Circular Economy (IKK) at Leibniz Universität Hannover, three 2nd-generation polymers and different blends of them were tested for biodegradability in laboratory tests (Neudecker, 2023). After 400 days, the tested materials showed a biodegradability of approximately 50–80% in a marine environment. But the results of such tests depend strongly on test conditions and materials. For example, the estimated lifetime for a PHA plastic bottles in the marine environment ranged from 1.5 to 3.6 years within eight studies (Dilkes-Hoffmann et al. (2019), cited by SAPEA – Science Advice for Policy by European Academies, 2020, p. 87).

Studies have also been carried out on degradability in soil and compost: "The 2nd generation polymers such as PBS, PLA, PBAT, PHA, PBSA as well as lignin, cellulose (acetates) and starch are certified as biodegradable for industrial composting plants on the basis of laboratory tests. However, in the environment, i.e. in the soil ……, mainly cellulose, PHA and starch degrade completely in short periods of time" (EPA Network – Interest group on Plastics, 2018). Starch-based polymers are degraded after about 12 months in

Table 1
Test methods and pass criteria for biodegradability of synthetic polymer microparticles (except polymers in products for agricultural and horticultural applications).

Group	Type	Proof	Test method	Pass criteria
1	Screening test methods [a]	Ready Biodegradability	T1: OECD TG 301 B, C, D, F (OECD, 1992a) T2: OECD TG 310 (Headspace Test) (OECD, 2006)	60% mineralization measured, over 28 days, as evolved CO_2 or consumed O_2
2	Modified & enhanced screening test [b]	Ready Bio-degradability Biodegradability in Seawater	T1: OECD TG 301 B, C, D, F (OECD, 1992a) T2: OECD TG 310 (Headspace Test) (OECD, 2006) T3: OECD TG 306 (OECD, 1992b)	60% mineralization measured, over 28 days, as evolved CO_2 (allowed for T1 and T2 tests only) or consumed O_2
3	Screening test method [c]	Inherent degradation	T4: OECD 302C (modified MITI Test (II) (OECD, 2009)	≥70% mineralization measured as consumed O_2 or evolved CO_2 within 14 days
4	Screening test methods [d,e]	Degradation relative to a reference material [f]	T5: EN ISO 14852:2021 (ISO, 2021) T6: EN ISO 14851:2019 (ISO, 2019a) T7: EN ISO 19679:2020 (ISO, 2020) T8: EN ISO 18830:2016 (ISO, 2016) T9: EN ISO 17556:2019 (ISO, 2019b) T10: EN ISO 22404:2019 (ISO, 2019c)	Ultimate degradation of ≥90% relative to the degradation of the reference material within: **6 months** in aquatic tests, or, **24 months** in soil, sediment or water/sediment interface tests
5	Simulation test methods [g]	Demonstration of degradation under relevant environmental conditions	T11: OECD TG 307 (OECD, 2002a) T12: OECD TG 308 (OECD, 2002b) T13: OECD TG 309 (OECD, 2004)	The degradation half-life in marine, fresh or estuarine **water** is less than 60 days. The degradation half-life in marine, fresh or estuarine **sediment** is less than 180 days. The degradation half-life in **soil** is less than 180 days.

[a] The 10-day window requirement mentioned in the T1 and T2 test guidelines does not need to be fulfilled.
[b] For group 2 test methods, the test duration can be extended to up to 60 days and larger test vessels used.
[c] The pre-adaptation of the inoculum mentioned in the T4 test guideline shall not be allowed.
[d] T5. 'Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium – Method by analysis of evolved carbon dioxide.' (EN ISO 14852:2021); T6. 'Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium – Method by measuring the oxygen demand in a closed respirometer.' (EN ISO 14851:2019); T7. 'Plastics – Determination of aerobic biodegradation of non-floating plastic materials in seawater/sediment interface – Method by analysis of evolved carbon dioxide' (EN ISO, 19679:2020); T8. 'Plastics – Determination of aerobic biodegradation of non-floating plastic materials in seawater/sandy sediment interface – Method by measuring the oxygen demand in closed respirometer' (EN ISO, 18830:2016); T9. 'Plastics – Determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved' (EN ISO 17556:2019); T10. 'Plastics - Determination of the aerobic biodegradation of non-floating materials exposed to marine sediment – Method by analysis of evolved carbon dioxide' (ISO 22404:2019).
[e] For group 4 test methods, the pre-adaptation of the inoculum shall not be allowed.
[f] The following materials may be used as reference materials:- positive controls: biodegradable materials such as micro-crystalline cellulose powder, ashless cellulose filters or poly-β-hydroxybutyrate.- negative controls: non-biodegradable polymers such as polyethylene or polystyrene.
[g] T11. 'Aerobic and Anaerobic Transformation in Soil' (OECD TG 307), T12. 'Aerobic and Anaerobic Transformation in Aquatic Sediment Systems' (OECD TG 308), T13. 'Aerobic Mineralization in Surface Water – Simulation Biodegradation Test' (OECD TG 309).
(Source: Own compilation based on European Commission, 2023a)

favorable conditions. For PLA-based materials, degrees of degradation vary considerably, from not at all up to completely degraded after 24 months (EPA Network – Interest group on Plastics, 2018). E.g., the thickness of the material has great influence on the degradation rate – the thicker the material, the less degradation takes place (EPA Network – Interest group on Plastics, 2018).

In sum, the 2nd generation is a major step forward, precisely because the focus has been mainly on natural substances. However, there is no comprehensive standard that regulates the performance of this group of substances and, in our opinion, there is still room for improvement to ensure the highest possible degradability after the use phase, particularly in sensitive marine ecosystems.

3.4. Methods of measuring and testing biodegradability

3.4.1. Laboratory analyses

In recent years, test models for laboratory tests have been developed for many different degradability tests (OECD 301 A, 301 B, 301 D, 301 F, 302 B, 310, see Table 1). Established tests for the environmental conditions of composting, soil, freshwater and seawater are also available specifically for water-insoluble plastics (Composting: ISO 14855-1, soil: ISO 17556, aqueous medium: ISO 14851 and ISO 14852, marine environment: ASTM D6691).

“Standard test methods for the biodegradation of plastic materials were introduced for compost in 1992 (ASTM D5338-15, 2015), for soil in 1996 (ASTM D5988-18) and 2003 (ISO 17556:2019, 2019), for the sea in 1993 (ASTM D5437-93, 1993; weathering only, no true biodegradation test) and 2009 (ASTM D6691-17), and for aqueous media in 1999 (ISO 14852:2018, 2018; focus on waste water treatment) … (and ISO, 18830:2016 at the marine seawater/sediment interface)" (SAPEA – Science Advice for Policy by European Academies, 2020).

With the aid of radioactive labeling, it is also possible to determine exactly how degradation takes place over time. It is possible to determine which paths the radioactive carbon takes over the test period (air, water, microorganisms).

The laboratory test provides results on whether plastics are in principle degradable. Bottle tests of up to several liters are commonly used. These tests are more transferable to the real situation in the environment if the test liquid is adapted as closely as possible to the conditions of the respective open environment (inoculum, chemistry, temperature, etc.).

Aerobic biodegradation takes place with oxygen consumption and CO_2 release. Both can be measured in laboratory experiments to track the degradation.

However, as mentioned, a proportion of the decomposed carbon is also converted into biomass in the microorganisms. Depending on the substance and microorganism, this can range from a few to several 10%. This carbon in the biomass can only be determined with very high analytical effort. For this reason, so-called blank tests (positive control with cellulose) have been used in the standards to quantify this biomass.

3.4.2. Aquarium and tank tests as well as outdoor tests

The results of laboratory tests have been criticized because they do not adequately reflect reality in the open environment, particularly aquatic environmental media (Gartiser et al., 2017). In order to capture the real conditions more accurately, the laboratory test can therefore be supplemented by tests under real environmental conditions (aquariums, tanks or field tests) (IKK – Institut für Kunststoff- und Kreislauftechnik, 2024). Fig. 3 shows the interaction of these test methods.

In contrast to the laboratory test in a bottle, the release of CO_2 from the decomposition cannot be measured exactly in the tank, even more so in the real environment. Observing or measuring the disintegration of the article has proven to be a good idea here. In this way, requirements could be formulated that determine the removal at the surface (in μg/a or mm/a) for an end product or the loss in cm^2/a for a film. Time-based requirements for disintegration can therefore also be set for tank tests, for example until half of the compound is no longer present.

3.4.3. Categories of biodegradability

As mentioned, organizations like the OECD and the International Organization for Standardization (ISO) offer different tests for analyzing biodegradability (ECHA – European Chemicals Agency, 2019a). These vary in duration and percentage of biodegradation (measured e.g. as percentage of the theoretical O_2 demand). The differences between the three types of degradation are (Filiciotto and Rothenberg, 2021):

- Readily degradable: 60% degradation (minimum) within maximum test duration (28 days); parameter measured: CO_2 evolved or O_2 demand; standards are OECD 302, 306, 310.
- Inherently degradable: 70% degradation (minimum) within maximum test duration (14 days); parameter measured: DOC (dissolved organic carbon) or BOD (biological oxygen demand) analysis; standards are OECD 302 B or 302 C.
- Ultimately degradable: 90% degradation (minimum) within maximum test duration (6 months (aqueous), 24 months (soil, seawater/sediment); parameter measured: CO_2 evolved or O_2 demand; standards are ISO 14851, 14852 (aqueous), 17556 (soil), 19679, 18830 (seawater/sediment).

Initiated on the basis of Article 69 (1) of the REACH Regulation, the European Chemicals Agency (ECHA) has prepared restriction dossier on 'microplastics' (ECHA – European Chemicals Agency, 2019a; ECHA – European Chemicals Agency, 2019b). Following this dossier, three categories for aerobic degradation can be distinguished (based on different OECD Testing Guidelines (TG) and ISO standards, see above):

- Ready biodegradability: “an arbitrary classification of chemicals, which have passed certain specified screening tests for ultimate biodegradability; these tests are so stringent that it is assumed that such compounds will rapidly and completely biodegrade in aquatic environments under aerobic conditions."
- Inherent biodegradability: “substances are classified as of chemicals for which there is unequivocal evidence of biodegradation (primary or ultimate) in any test of biodegradability.
- Ultimate biodegradability:
  - “breakdown of an organic compound by microorganisms in the presence of oxygen into carbon dioxide, water and mineral salts of any other element present (mineralization) plus new biomass” OR
  - “test compound is totally utilized by micro-organisms resulting in the production of carbon dioxide, water, mineral salts and new microbial cellular constituents (biomass)".

Based on ECHA’s restriction dossier on ’microplastics’ (ECHA – European Chemicals Agency, 2019a), the European Commission adopted measures that restrict synthetic polymer microparticles intentionally added to products under the EU chemical legislation REACH in September 2023 (European Commission, 2023a). The intentionally added polymer microparticles include synthetic polymer microparticles for use in the encapsulation of fragrances; in ‘rinse-off products’ for use as an abrasive, i.e. namely to exfoliate, polish or clean (‘microbeads’); lip, nail and make-up products; leave-on products; detergents, waxes, polishes and air care products; medical devices; fertilizing products; plant protection products and seeds treated with those products, and biocidal products; other products for agricultural and horticultural uses; granular infill for use on synthetic sports surfaces. The referring Annex contains three test method groups with screening tests measuring ready biodegradation or inherent biodegradation, and specifications for simulation studies for testing biodegradability in water, soil and sediment. Table 1 gives a survey on the test methods and pass criteria (except polymers in products for agricultural and horticultural applications).

Tests of group **1 to 3** are used to determine whether a substance is readily or inherently degradable. “Inherent tests are performed under more favorable conditions and thus give useful information whether any potential for biodegradation exists irrespective of their relevance for environmental compartments. Results from inherent biodegradation tests may be used for assessing persistency in two ways. First, test results above 70% are used for indicating ultimately biodegradability and are used as trigger for non-persistency when specific criteria (log phase no longer than 3 days, pass level reached within 7 days) are met. Second, negative results from inherent tests (<20% DOC-elimination) indicate a high probability for environmental persistence” (Gartiser et al., 2017, p. 81–82).

“Meeting the pass criteria in any of the permitted test methods in **groups 1 to 3** is sufficient to demonstrate that the polymer or polymers contained in the tested material and subject to the test are degradable and are therefore excluded from the scope of entry … *(of the Annex)*". Any of the permitted test methods implicates, that it is sufficient if only one of the four test methods is used. “Where **group 4 or group 5 tests** are used to demonstrate degradability of polymers for uses other than agricultural and horticultural uses, the pass criteria shall be met in three environmental compartments”: water, soil and sediment, here: (a) fresh, estuarine or marine sediment; **or** (b) fresh, estuarine or marine water/sediment interface (European Commission, 2023a). The effort required here is higher than in groups 1 to 3. The methods in groups 4 and 5 are therefore more likely to be used if the pass criteria for the methods in groups 1 to 3 are not met.

4. ‘Safe and sustainable by design’ (SSbD) – third-generation biodegradable plastics

4.1. The concept of SSbD

Regarding plastic removal technologies (PRT, see Section 2.2) Bergmann et al. (2023) point out that the most effective and cost-efficient way to prevent plastic pollution is to replace unsafe, unsustainable and nonessential plastic chemicals, polymers, and products from the economy.

‘Safe and Sustainable by Design’ offers a concept for the development of innovative chemicals and materials (European Commission, 2022a). The aim is to ensure that sustainability is also taken into account during product development. A key criticism is that product developers and chemical inventors only or primarily think about the benefits of the product in the use phase, with little regard for ecological impacts. The ‘Safe and Sustainable by Design’ approach seeks to shift this mindset. One of its core principles, ‘design for end of life’, includes biodegradability (European Commission, 2022a, p. 187):

- Definition: Design chemicals and materials so that, once they have served their purpose, they break down into chemicals that do not pose any risk to the environment or to humans.
  Design chemicals and materials in a way that makes them fit for re-use, waste collection, sorting and recycling/upcycling.
- Examples of Action: Avoid using chemicals or materials that impede end-of-life processes such as recycling. Select materials that are: …
  d. Fully biodegradable for uses that unavoidably lead to release into the environment or wastewater

‘Safe and Sustainable by Design’ is future-oriented and visionary. This includes the possibility to formulate requirements that are not yet met by existing options. We call this development ‘third-generation’ degradable plastics or compounds. Third-generation plastics will have to be the result of a new regulation we propose here. If the legislator in Europe demands a defined degradability for plastics such as microplastics or packaging films, these plastics must be optimized to meet this objective (‘Safe and Sustainable by Design’). This can also be achieved on the basis of the second-generation plastics, but there may also have to be new developments.

These questions can only be answered once a standard for the third-generation has been set. This standard will have to be different for the respective relevant media: seawater (North Sea, Mediterranean, tropics), fresh water, soil. The standard should not be derived according to the possibilities of the second-generation degradable plastics, but should be found according to the necessities of environmental protection in the media mentioned. The EU regulation for microplastics described in Table 1 provides a good basis for this standard. Based on this standard, approval procedures should be used to clarify which polymer or compound meets the new standard. The approved degradable plastics or compounds then form the basis for the substitution of 'forever' plastics. What should be substituted is explained below.

This leads to the central question: Why should this substitution be carried out? There is a whole series of life cycle assessment studies that present the advantages (e.g. climate protection) and disadvantages (e.g. agricultural emissions) of today's second-generation degradable plastics. For us, the overriding reason for further development are **the harmful effects of emissions on human health and the environment – especially marine environment**. And the chemical industry's raw material transition (see next paragraph) will only partly be based on biomass, which does not have to be produced agriculturally in principle.

In 2023, the German Chemical Industry Association (VCI) and the Association of German Engineers (VDI) (VCI and VDI, 2023) published their thoughts on the raw materials transition, emphasizing the importance of plastics recycling for the raw materials transition. "The three different scenarios were analyzed: 1) focus on maximum direct electricity use, 2) focus on hydrogen and PtX fuels and raw materials, and 3) focus on secondary raw materials (plastic waste and **biomass**). As a result, scenario 3 would have a maximum CO_2 requirement of half that of the other two scenarios and would only require two thirds of the investment required for the raw materials transition. The authors of the study therefore propose developing the existing recycling quotas into substitution quotas, which VCI/VDI also call 'closed-loop quotas' (Lahl, 2024)". The defossilisation of the plastics industry, which is necessary for climate protection reasons, can therefore provide synergies for the ramp-up of degradable plastics (use of biomass).

It can certainly be criticized that we are proposing something – a third generation – that does not even exist today. We would like to initiate a scientific discussion on the question of what requirements degradable plastics should actually fulfill from a marine environmental protection perspective. But how else can 'Safe and Sustainable by Design' work if we don't set requirements that have to be met in future? The standard should primarily be set in such a way that there is a substantial improvement on the current situation. The requirement could certainly be ambitious. If there are no plastics that meet this standard, then our proposal would have failed. In the event of failure, we would then be referred to the current status quo: i.e. no deterioration. If the proposal does not fail, we would have achieved a significant improvement in some areas.

Is this approach not unusual, perhaps even uncharted regulatory territory? Quite the opposite: there are many examples, particularly at EU level, where the spirit of 'Safe and Sustainable by Design' is ambitiously conceived, but which has yet to be technically developed or achieved. Environmental legislation or climate protection often works in this way. For example, CO_2 reduction quotas are standardized for e-fuels, the implementation of which has yet to be developed. The eco-design regulation (Regulation (EU) 2024/1781, 2024) has proposed standards that must in future be implemented technically by the European Commission and industry. In the past, some emission limits were set for e.g. industrial plants or cars where the necessary technology had to be (and was) developed afterwards.

Anyone analyzing developments in conventional plastics will notice how the design of products has become increasingly refined and improved over the last few decades. Today, a simple film for packaging of meat or cheese consists of several different layers that turn this film into a high-tech product ('system solution'). This design potential will also be necessary for degradability in different media (third-generation).

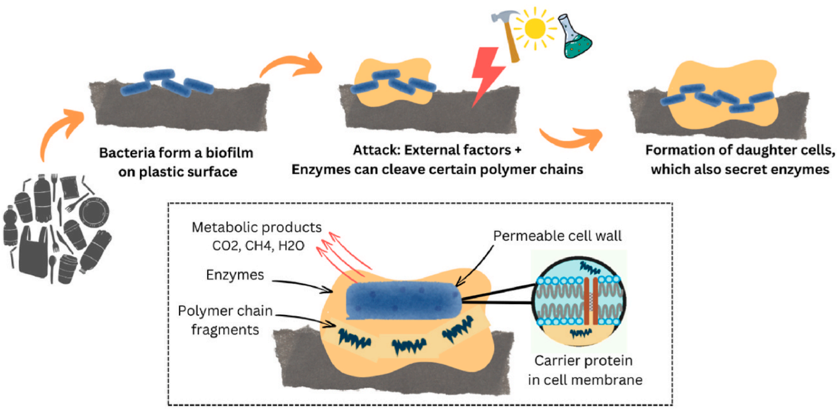

Fig. 4. The figure shows the principle of the degradation of biodegradable plastics. Bacteria form a biofilm on plastic surface. The surface is attacked by external factors (e.g., UV radiation, mechanical forces, heat or chemicals) plus bacterial enzymes, which can cleave certain polymer chains. The bacteria grow and multiply by formation of daughter cells, which then also secret enzymes.

4.2. Requirements for biodegradability

4.2.1. Biodegradability in water

Lower concentrations of microorganisms are found in aquatic environments (freshwater, seawater, sediments) than in soil or even compost (see below). The microflora here consists mainly of bacteria and not, as in soil, of fungi, which make up the majority of the decomposition process there. Marine-compatible degradable plastics, for example, would therefore be polymers that are degraded by microorganisms in the various marine ecosystems. The tests must therefore be modeled on these respective environmental conditions.

The degradation of a plastic product in the sea begins with the colonization of a biofilm on the surface of the plastic part (Fig. 4). The biofilm contains a wide variety of microorganisms, which also work together. Extracellular enzymes are present in the biofilm, which can carry out the first degradation steps on the polymer. Intracellular degradation processes are, as explained, not yet possible at this stage. The advantages of biodegradable plastics lie in the shorter time required for extracellular degradation.

Both, the scientific community and the European Commission, rightly point out that the degradability of the respective polymer molecule and the degradation performance of the respective receiving ecosystem must be considered together (SAPEA – Science Advice for Policy by European Academies, 2020; European Commission, 2022b). The Commission also stipulates the boundary condition that degradable plastics must not form any intermediate products during degradation that cause new problems. The rate of degradation must in addition be so high that no accumulation of intermediates in organisms can occur (Directive (EU) 2019/904, 2019).

4.2.2. Biodegradability in soil

There are also differences in terms of degradability in soil or compost. Over 90 different types of microorganisms – mainly fungi, but some bacteria, too – capable of digesting biodegradable plastics have been identified in soil and compost. The diversity of microorganisms found in water bodies is smaller (EPA Network – Interest group on Plastics, 2018).

Plastics for the agricultural sector such as agricultural films should be degradable. For instance, fossil-based plastics made of polybutylene adipate terephthalate (PBAT) are completely degradable (Yang et al., 2023) and can replace non-degradable plastics such as PE in agriculture.

4.2.3. Biodegradability in other environmental media

In addition to the marine environment and the soil, there are a number of other environmental media that are relevant for degradable plastics. These include freshwater biotopes. However, anaerobic media such as bogs or sediments can also be relevant.

4.2.4. The example of detergent pods

Detergent pods have now established themselves on the global market. They have a number of advantages over powder detergents, which will not be discussed in detail here. Pods or caps are coated with a plastic, consisting of polyvinyl alcohol = PVA. It has special properties, e.g. it dissolves very quickly in water. This is why the pods dissolve the detergent in the wash liquor even at low washing temperatures of 40 or 30 °C. The pod itself is then not yet degraded, but enters the wastewater with the washing liquor in dissolved form. In solution, PVA can be biodegraded very well in sewage treatment plant, the degradation is complete (Byrne et al., 2021), if the conditions are at optimum, as they are in the degradation tests.

The pods are an example of how the littering problem could be tackled in principle through adapted polymer chain design. Due to the very rapid dissolution, the formation of macro- and microplastics is virtually skipped and the biological attack in the solution itself is significantly facilitated. And the alcohol groups (or ester groups) provide the microorganisms with the points of attack for biodegradation.

In the United States, NGOs have publicly criticized the pods for their plastic coating and feared inadequate degradability. In Germany, the NGO World Wildlife Fund (WWF) is – in cooperation with Procter & Gamble – promoting the pods because of their ability to lower the washing temperature and thus save energy and CO_2 emissions (WWF, 2023).

The example of pods shows what chemical modifications to the polymer molecule can achieve. Today, PVA is of purely fossil origin, but can also be produced from non-fossil sources. In principle, PVA is chemically similar to degradable natural polymers such as carbohydrates.

The design requirements for food packaging, for example, are different to those for the pods' detergent packaging. But the example of pods shows the spectrum available for the design. The requirements for the third-generation will have to be defined between these extremes (immediate dissolution and rapid degradation, delayed dissolution and slower degradation).

5. Specifications for third-generation biodegradable plastics

5.1. Application area

One reason for postulating a third-generation is to select the best and to further shorten degradability in the open environment. Degradable plastics are not a 'silver bullet' for solving all plastic problems. They would fail with this claim. They can only provide a solution for those products that enter the environment (marine or soil) as intended or are difficult to prevent from doing so. In our opinion, the following plastics should therefore - as a first step - be addressed in innovation efforts to become biodegradable:

1. All microplastics that may continue to be used in consumer products such as cleaning agents, scouring salts or cosmetics and care products (e.g. toothpaste) (in the EU already addressed by Commission Regulation (EU) 2023/2055 (European Commission, 2023a), see Section 3.4.3),
2. All microplastics that are used in paints, varnishes, coatings and sealants for the construction sector and are subject to intensive weathering,
3. Rubber articles that are released into the environment as microplastics to a relevant extent during use,
4. Other plastic articles or fabrics that are subject to intensive abrasion during the use phase (cleaning cloths, sponges, drying cloths, cleaning rags, etc.),
5. Agricultural plastic products such as seed and fertilizer wrappings, thin mulch films, plant seedings, tree shelter tubes that are not removed from the soil (SAPEA – Science Advice for Policy by European Academies, 2020), (in the European Union already addressed by Regulation (EU) 2019/1009 (2019) and Commission (EU) 2023/2055 (European Commission, 2023a),
6. Fishing nets (especially trawls) and other plastic products for fishing/angling (De Domenico et al., 2023),
7. Textiles for intensive use in water (such as mats, splash guards, swimsuits, etc.)
8. Small plastic parts such as firework casings (SAPEA – Science Advice for Policy by European Academies, 2020),
9. Selected volume-relevant food packaging (Cowger et al., 2024),
10. Other disposable articles (e.g. cigarette butts (Araújo and Costa, 2019)).

For product of the groups 1 to 9, it must be assumed that they are released into the environment more or less as intended or whose release cannot be prevented to a sufficient extent (cigarette butts). This means that these areas of use are not available for other solution strategies such as waste management. Therefore, there is no solution strategy for these products other than degradability (except for a ban). For textiles, it is assumed here, that fabrics made from natural fibers meet the requirement for degradability. And for rubber articles such as tires, neither a ban nor degradability will be a solution. Here, we will have to think about secondary solutions such as cleaning the road runoff.

Products of group 9 would potentially be available for recycling. It is therefore necessary to examine how the degradability of these products harmonizes with the circular economy. Food packaging, e.g., does not end up in the environment as intended, but it still accounts for the majority of littering. The littering of plastic packaging appears today to be impossible to prevent. We therefore propose a decision on which packaging is particularly relevant for marine litter and should therefore be biodegradable, perhaps starting with selected brands.

Disposable items should certainly be banned wherever possible, which the EU has already started to do (single-use plastic products (SUPs) (Directive (EU) 2019/904, 2019). “Specifically, before considering BDPs *(biodegradable plastics)* for certain applications, it is important to consider whether the application should exist in the first place, or if alternatives materials could be employed instead” (European Commission, Group of Chief Scientific Advisors, 2020). Where this does not appear to be technically or politically feasible, degradable plastics could provide a solution, especially in cases where the benefit is great (e.g. thin mulch films, slow-release fertilizer).

5.2. Third-generation biodegradable plastics – standards and testing

Following the Science Advice for Policy by European Academies (SAPEA), the testing and certification should not be limited to only the polymer(s) that constitute the plastic in those cases where the properties of the plastic material are largely affected by additives (SAPEA – Science Advice for Policy by European Academies, 2020). Instead, the actual plastic material or even the final commercialized plastic item containing the additive should be tested.

For the laboratory test of the third-generation plastics, the material should be crushed to microplastic size. This can be used to test:

- whether a plastic is degradable at all in a short time,
- whether microplastic degradation is inhibited and can therefore pose a problem.

We suggest using the ECHA recommendation (ECHA – European Chemicals Agency, 2019a; ECHA – European Chemicals Agency, 2019b) to determine the exact standard. These limits already apply to intentionally emitted microplastics. The standards for others like packaging and disposable items could be derived on this basis. And tank tests can be carried out for this purpose as a safeguard. Here the test is carried out in film form. In the tank test, the disintegration of a defined test specimen from the plastic should be achieved in a defined time (half-life).

On the basis of the standards mentioned above, plastics in the form of a compound (polymer and additives) can apply for approval and submit the necessary application documents. After examination by the relevant EU authorities (e.g. ECHA), approval is granted as a biodegradable plastic (compound). Labeling is then carried out on this basis. In our opinion, others labels should then be phased out.

The expected innovations will also be achieved by mixing polymers (blends) and using additives (compounds). For the latter, it is important that high requirements are also set for the safety of the additives used for the third-generation. As the third-generation of degradable plastics does not have to be ‘forever’ stable, it is also possible to achieve the desired properties using natural substances as additives (Rennert, 2024).

5.3. Significant improvement quickly achievable

Of course, the exact requirements for the third-generation plastics have not been defined and need to be derived by the legislator resp. standard setter (IKK – Institut für Kunststoff- und Kreislauftechnik, 2024). But the Commission Regulation (EU) concerning synthetic polymer microparticles (European Commission, 2023a) is, as said, an important document that can be built on. An optimal standard would be if microplastics were already **largely** degraded in sewage treatment plants.

Packaging must not disintegrate during the service life. However, it is quite possible to set a shorter half-life: one month or one year. Would it be acceptable for the disintegration of packaging in the sea to only be half complete after one year? (This means, that after ten years, 99.9% of the initial mass will be disintegrated.) This is ambitious from the point of view of functional packaging. However, this would still be a long residence time in the environment. But to appreciate such an ambitious requirement, one must recognize the qualitative difference between biodegradable and 'forever' plastics. Even if intact third-generation films in the open environment are only half degraded after one year, this is hundreds of times better than the current situation. What may appear to be a long period of time at first glance must be compared with today's 'forever' plastics, which are not degradable for hundreds of years.

From 2026, the European Commission has required 90% degradability in soil within four years for polymer coatings in slow-release fertilizers (European Commission, 2023a). And degradability is also required for many other applications with different deadlines within the next ten years. A significant amount of innovation, therefore, can be expected to be developed and deployed over the next few years. So, while our proposals are ambitious, they are neither regulatory nor politically unrealistic as a starting point for discussion about 'Safe and Sustainable by Design'.

5.4. Ecological objections against substitution

The problem with plastics is a complex one and a combination-approach is needed. There are reputable voices who reject biodegradable plastics on the grounds that these products make littering acceptable and encourage consumers to litter carelessly. At first glance, these worries are not unjustified. Whether and to what extent this can actually occur with the introduction of a third-generation will depend largely on how the solution strategies are **communicated**. In addition to communication, the overall strategy is also important: how is degradability embedded in the other objectives of the circular economy, and how credible are those commitments?

In terms of chemical policy, this is not the first time that there have been calls for better substitutes. Until now, those who have spoken out against chlorine chemistry or foam piles on rivers and advocated substitutes with better properties (e.g. lower persistence) have not been assumed of wanting to ease environmental pollution with chemicals. It is true that once substitution has taken place, the better properties of the substitute could theoretically be used to generate an argument that the substitute should be handled less sensitively. But communication about environmental risks does not stop once substitution has taken place. And it is wrong to assume that the substitutes will be so good that they will instantly 'vanish into thin air' after coming into contact with seawater. On the contrary: as we have shown, the substitutes remain visible in the environment for months and are completely degraded only after a few years. So, there are good reasons to justify continued communication against littering.

Then there is the fear that degradable plastics, like 'forever' plastics, also produce microplastics. This is also a legitimate concern. But there are differences here, too. Both types of plastic disintegrate at different rates. When microplastics keep the pass values of biodegradability tests as set by Commission Regulation for microplastics (European Commission, 2023a) (see Table 1), for example, the survival times of biodegradable microplastic particles are short. This is quite different for 'forever' plastics, where these particles survive for centuries.

Another ecological argument against substitution is that the degradation of the polymer chain with the resulting intermediates (metabolites) could give rise to new risks. It is initially in the logic of degradability that degradation only occurs via metabolites. The degradable second-generation plastics have not yet shown any risky metabolites because they were designed on the basis of natural substances and are therefore degraded via metabolites such as sugar or lactic acid. The degradation chemistry of many degradable polymers is also not highly complex (Haider et al., 2019). And risks can be identified through development work and accompanying investigations, close monitoring and much more. For synthetic polymers that do not occur in nature, this aspect will have to be examined more closely - a test that is routine as part of an approval procedure for new chemicals.

But let's make the abstract political assumption that there is a defined risk X. One argument for this could be that we can never know everything and that the third-generation is yet to be invented. With all new pathways, society needs to mitigate risks. There is no development without accompanying risks. In essence, it is a question of the (political) standards for the extent to which risks are taken. Nanotechnology is an exciting example. Fifteen years ago, the German government set up the so-called nano dialogue involving the relevant stakeholders. All sides worked transparently on the risks, but also recognized and evaluated the opportunities for environmental protection. **Risks were accepted because the opportunities of this new technology, this chemical development, outweighed the risks**. Applied to the subject of this article: Even if there were risks for substitution, these must be weighed against the benefits that a solution to the littering problem would bring.

It would not be the first time that risks have been taken in the face of opportunities. The entire chemical policy history of the substitution of hazardous substances is a history of balancing opportunities and risks. So, is it all a question of scale, what risks are taken? For example, the environmental risk of mining lithium in South America and China have come to attention recently and are considered manageable because even many NGOs believe that the opportunities of electromobility to combat climate change outweigh the risks.

And industry? It's in the interests of the economy that it does not march ahead in the substitution of fossil plastics and prefers to maintain its existing value chains. Even if industry has started to develop degradable plastics at the same time, this is not currently a main area of research and development.

Another conceivable objection would be that the development of a third-generation would take far too long. How quickly could marine-compatible plastics be available? Ten years ago, we were given a timeframe of 10–20 years by the industry (Zeschmar-Lahl and Lahl, 2014). In the meantime, a lot has been developed in this field, but the concentrated innovation potential of industry and science has not been unleashed. Ambitious regulation should allow a development period of around five to ten years, similar to that for slow-release fertilizers in the agricultural sector and the microplastics regulation. A gradual substitution, s could therefore take place from 2030 on.

And then there is another objection from the waste management industry: In developed waste management systems degradable plastics would disrupt waste management. But for most areas of the intended application (Section 5.1) this is not relevant, as these products or parts of them do not reach the waste management sector at all – they end up in the environment as intended. These products release microplastic in the course of their utilization (loss is intrinsic to use: e.g. tires, shoes, textiles), or they end up in the environment as intended (e.g. agricultural plastic products), or their release into the environment can foreseeably not be reduced to the necessary extent (high risk of loss: e.g. fishing nets, cigarette butts) (SAPEA – Science Advice for Policy by European Academies, 2020).

The situation would be different if, for example, our recommendation to produce important disposable packaging from degradable plastics, were also followed. How this would affect waste management must be considered for the point in time when the third-generation plastics become waste to a relevant extent and for waste management in its then existing form (2030 and beyond). We take a critical view of whether the material recycling of separately collected **mixed** packaging will still be viable at this time (Lahl et al., 2024a, 2024b).

It can be assumed that the current unsatisfactory state of material recycling will lead to further regulatory and technical developments from 2030 on as a result of climate protection requirements (Lahl et al., 2024b). Degradable plastics for important packages, which would only ramp up at this time, can therefore be integrated into these developments (e.g. substitution quotas or more chemical recycling) (Rosenboom et al., 2022). In the end, this leaves no relevant reason for rejection from the waste management sector.

Although developing and emerging countries make up the majority of the world's population, they do not have sophisticated recycling structures. Here, the central facility is the 'wild' (uncontrolled) or sanitary landfill. If this situation does not change, degradable third-generation plastics will act like biological matter, like paper or wood. If landfill gas is collected, the degradation products will end up there proportionally. The additives of the third-generation plastics that will be less hazardous compared to those contained in today's plastics would be an advantage. We do not expect any major environmental differences if 'forever' plastics were to be substituted in the packaging sector. If plastics become a littering problem via the water path or drifting, the advantages of third-generation plastics would become apparent.

Then, there remains a climate policy objection. Degradable plastics are broken down into CO_2, which is known to be harmful to the climate. This also happens with 'forever' plastics, for example when they are incinerated. However, incineration generates energy as a byproduct, unlike the natural degradation process. Based on this reasoning, environmental pollution caused by 'forever' plastics might seem preferable to that of degradable plastics because they do not release CO_2 in the environment. On the other hand, we have to weigh up the great damage 'forever' plastic causes to the environment. And if microplastics really do have a negative impact on the nutrient cycles of the oceans, the objection becomes the opposite. Moreover, this climate objection would no longer apply if the degradable plastics were also bio-based.

If plastics were fully recycled through mechanical processes, another consideration – energy efficiency – comes into play, closely tied to the CO_2 argument. In a closed recycling loop, energy stored in plastics circulates rather than being lost. Since degradable polymers cannot be recycled, producing them repeatedly requires additional energy. However, this argument is less relevant for the specific applications recommended here, where the products are designed to be released into the environment and are thus unavailable for recycling. At most, this energy consideration could apply if degradable plastics were extended to certain high-volume packaging applications. Even in that scenario, the energy argument becomes significant only if recycling achieves high substitution rates for virgin plastic, a goal far from current reality. Should such recycling efficiencies be achieved in the distant future, we would still need to carefully weigh which solution – enhanced degradability or maximized recycling – takes precedence. But it is unrealistic to think that one can avoid everything.

This objection to degradable plastics leads to a very fundamental issue: wouldn't avoiding plastics be a better solution strategy? The answer here is a clear 'yes' (see Section 2.6.1). This solution strategy also has the psychological advantage of not having to make difficult trade-offs between a lesser and a greater evil. But every ton that we save on packaging waste is unquestionably superior to all other solution strategies. The other solution strategies are only relevant for disposable products or packaging that is not avoided.

Political and regulatory resources are also in short supply. Wouldn't it be better to leave the topic of 'substitution' and concentrate fully on the topic of 'avoidance'? In our opinion, this argument is supported by SDG 12 (responsible consumption and production), however it needs to undergo a reality check. The case of Germany, where the Green Dot was rhetorically introduced as a measure to reduce waste almost 30 years ago, waste avoidance success has been very limited with concluding thoughts on caution (Lahl et al., 2024b). But as climate protection remains a priority, we will also have to achieve success in terms of avoidance and sufficiency. However, there will still be sufficient need to implement solution strategies for the remaining plastic products.

Finally, we come to what is probably the biggest political mistake in the debate on solution strategies for marine littering: the 'prevention' solution strategy and the 'degradability' solution strategy are positioned as alternatives, perhaps even as opposites. All solution strategies should rather be seen as complementary to each other in a holistic and stringent combination approach.

5.5. 'Forever' plastics under review

On examination, the question arises as to why polymers such as PP or PE are not counted as persistent substances under substance legislation. One reason for this is that polymers are not covered by REACH, which was a political compromise at the birth of REACH. An extension of the REACH regulations to plastics would in any case have to include the emission relevance of the respective plastic products.

A discussion has currently begun in the European Commission to make relevant polymers subject to registration in REACH after all (European Commission, 2020a, 2020b). The Commission has prepared this intention through various studies and is now seriously in the process of structuring this addition to REACH (cefic, 2022). Polymers are to be tested to determine whether they are toxic to humans and the environment. The test criteria that have so far been expressed are

- the bioavailability,
- oligomers contained above specified limits,
- reactive groups that may be toxic,
- possible degradation to dangerous intermediates (cefic, 2022).

These criteria cover plastics that are subject to degradation in the organism or the environment. This can be relevant for defined polymers that have been formed via polycondensation, for example. This test would **also** be **relevant** for biodegradable plastics of the 2nd and 3rd generation. However, it is also important for environmental protection to determine the degradability of polymers and to develop regulations on this basis. In our opinion, two further hazard classes should be added to the range of hazard classes:

- damage to organisms by blocking the digestive system or causing inflammation of internal organs,
- damage to zooplankton through ingestion.

In the logic of REACH, the use of plastics that are not degradable must only be allowed in cases where their entry into the environment can be ruled out (for construction products, furniture, cars, for example). Ultimately, the REACH system would then require the substitution of non-degradable polymers (in particular PE, PP, PS, PVC and others) with degradable polymers in clearly defined areas of application (socio-economic assessment) for the particularly serious risks, especially where these plastics are released into the environment as intended. The ECHA has classified microplastics and nano-plastics as PBT (persistent, bioaccumulative and toxic) and vPvB (very persistent and very bioaccumulative) and, on this basis, recommended that the European Commission ban them. The Commission has essentially followed this in its regulation to ban microplastics. It will therefore be interesting to see whether the (new) Commission and its committees also take up the new task for macro-plastic with this issue of soil and marine protection.

5.6. Socioeconomic and political aspects

A substitution of 'forever' plastics would have winners, but also losers. The losers would be, for example, the polymer manufacturers of PE, PS, PP, PVC etc. But the ideal (waste) world described above would also have winners and losers. From a purely logical point of view, the envisaged closed cycle would mean that no new or a little virgin plastic would be needed. Since we are initially only proposing substitution for a part of the plastics market, the closed loop would have a harsher impact on polymer manufacturers than our proposal, again in purely logical terms. Plus, losers can also become winners. For example, the plastics industry can also produce degradable plastics, especially if this is required in larger quantities.

From an economic perspective, curbing overall demand for plastics will limit the costs of waste collection. Phasing out fossil fuels, as proposed on recent Conferences of the Parties (COPs) on climate change, could change the economics of plastic production towards secondary streams, in particular if smart policies such as Extended Producer Responsibility and Deposit-Return-Systems facilitate transformations. The OECD, however, raises concerns on additional economic burden in developing countries who need to invest more than many industrialized countries to upgrade their waste management systems (OECD, 2024b).

And, of course, things will also change for biodegradable food packaging. This packaging will no longer last 'forever' as it does today! Shorter cycles will have to be considered, fresher food will have to find its way to the consumer and supply logistics will have to change – a broad field for innovations and new business models. And the introduction of degradable packaging, like any other far-reaching technical regulation, will also be subject to exceptions. But in our opinion, this effort is worth it for the ecological goal.

5.7. Public perception and consumer behavior

Finally, the introduction of degradable third-generation plastics will also pose challenges for consumer education in the future, especially if packaging is included. While consumers are likely to support efforts to address plastic pollution by purchasing products with such packaging, practical drawbacks must also be considered. For example, shorter shelf lives, faster turnaround times and problems with food storage could occur. For this reason, we do not advocate for an immediate and comprehensive shift in the packaging sector. Instead, a targeted strategy that begins regionally, focusing on products most associated with littering, appears to be a more viable approach. However, the success of this initiative will depend heavily on intensive consumer engagement and education.

But it will not work without intensive consumer involvement (Kautish et al., 2021; van Oosterhout et al., 2023). The emergence of 'plastic smart cities' promoting shifts in consumer behavior while collaborating with local businesses is a promising signal. Scientific findings suggest a strong minority of 25% being able to trigger social changes and overturn prevailing majorities in social norms (Centola et al., 2018). Albeit beyond the scope of this paper, we suggest to include consumer behavior as a pillar in a combination approach to tackle marine plastic litter.

6. Conclusions

The issue of plastics, especially litter, is highly complex and requires a combination approach to address. Biodegradability is one potential contribution to the solution, and this article aims to highlight the importance of this perspective. However, this solution should focus in the beginning on materials that will inevitably enter the environment in the future. This limitation underscores the necessity of other established measures, such as waste management and a circular economy in general, which remain crucial despite their insufficiency, as demonstrated in this article.

Ultimately, it is about replacing step by step relevant 'forever' plastics by more sustainable alternatives. Plastics that are not degradable in nature are broken down into microplastics and nano-plastics. This process is irreversible, and we still do not know whether this is hazardous. In all countries of the world, large quantities of 'forever' microplastic particles continue to be released into the environment. Our paper underlines the opportunity to formulate requirements for plastics that would put an end to such unsustainable patterns by Safe and Sustainable by Design. The key to this is to define degradability in the open environment.

Till today, the biodegradable plastics on the market represent progress (second-generation) compared to the 'forever' plastics such as PE or PP. And 0.5% of the world's plastics on the market already belong to these plastics (more than 1 million tonnes per year (European Bioplastics, 2023). This process is certainly dynamic (European Bioplastics, 2022). But development work needs to go further so that we can obtain plastics that are sufficiently stable in the use phase and that degrade in the (marine) environment in a sufficiently short time (third-generation). The third-generation builds on the second-generation plastics, but can also include completely new plastics. Hence, we call for more disruptive innovation in an emerging novel supply chain.

In this perspective the polymer molecules are no longer 'forever' stable, but are metabolized in shorter times, and the additives in the plastic do not serve to protect against degradation, they will be released much faster than is currently the case with 'forever' polymers via migration. For this reason, a very high safety standard must apply to degradable plastics in terms of additives (inherently safe substances). However, this is possible because the third-generation has to be developed newly and therefore no substances from previous cycles (legacy chemicals) are carried over.

From a regulatory perspective, it is anticipated that degradable plastics will be recognized as one of several strategies to address plastic pollution during the international negotiations on a Global Plastics Treaty. As part of the negotiations on this treaty, the topic is being addressed positively under the term 'alternative' plastics. This is also supported by the scientific community (Bleischwitz, 2022; Scientists' Coalition for an Effective Plastics Treaty, 2023).

The delay and some disappointment with the negotiations on a Global Plastics Treaty (European Commission, 2024) underscore the importance of adopting a combination approach to avoid reaching a stalemate ending up empty-handed. We therefore recommend that the third-generation of degradable plastics proposed here should be given even greater focus by the scientists and other stakeholders involved in the forthcoming negotiations.

Regardless of the final outcome of those negotiations on a Global Plastics Treaty, the EU could develop a regulation that would set an example for other regions. The starting point for this would be the European Strategy for Plastics in a Circular Economy (European Commission, 2018). The Strategy recognizes that ' … biodegradable plastics can certainly have a role in some applications and the innovation efforts in this field are welcomed', and identifies the need for a clear regulatory framework for plastics with biodegradable properties (European Commission, 2018).

In future, the EU will have to step up its efforts to make key industries climate-neutral (European Scientific Advisory Board on Climate Change, 2024). This includes, in particular, the necessary raw material transition in the chemical industry (feedstock change) (Lahl and Zeschmar-Lahl, 2011; VCI and VDI, 2023; Lahl and Zeschmar-Lahl, 2024a, 2024c; Lahl et al., 2024a) away from fossil raw materials such as crude oil and natural gas and towards recycling, materials from CO_2 and renewable energies and raw materials from biomass. This raw material transition will also provide a major economic tailwind for the market launch of degradable and biomass-based plastics, for example. In a perspective, the EU may coordinate efforts with other countries and like-minded industries operating at international scales.

CRediT authorship contribution statement

Rebecca Lahl: Writing – review & editing, Visualization, Investigation, Conceptualization. **Raimund Bleischwitz:** Writing – review & editing, Validation, Conceptualization. **Uwe Lahl:** Writing – original draft, Conceptualization. **Barbara Zeschmar-Lahl:** Writing – review & editing, Visualization, Investigation.

Data Availability

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Glossary

Biodegradable, readily	OECD: 60% degradation (minimum) within maximum test duration
Biodegradable, inherently	OECD: 70% degradation (minimum) within maximum test duration
Biodegradable, ultimately	90% degradation (minimum) within maximum test duration
Macroplastics	Plastics with a diameter of 5 mm and more
Microplastics	Plastics smaller than 5 mm
Nano-plastics	Plastics size of less than 1 μm (<0.001 mm)
Primary microplastics (‘microbeads’)	Microplastics produced industrially and intentionally added to products used for technical purposes (e.g. as abrasives) or as cosmetics (peelings, toothpaste) or cleaning agents
Secondary microplastics	Result of fragmentation of macroplastics (e.g. abrasion of tires and markings on roads, washing of textiles, mechanical treatment of plastics).

Abbreviations

BDPs	Biodegradable Plastics
BOD	Biological Oxygen Demand
DOC	Dissolved Organic Carbon
ECHA	European Chemicals Agency
EPR	Extended Producer Responsibility
EU	European Union
GPML	Global Partnership on Marine Litter
MP	Microplastics
Mt	Million tonnes (or Megatonnes)
OCS	Operation Clean Sweep®
OECD	Organisation for Economic Co-operation and Development
PBT	persistent, bioaccumulative and toxic
PRF	plastic recycling facility
PRTs	Plastics removal technologies
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SSbD	‘Safe and Sustainable by Design’
t/a	Tonnes per year
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environmental Programme
vPvB	very persistent and very bioaccumulative

Polymers

PBAT	Polybutyrate adipate terephthalate
PBS	Polybutylene succinate
PBSA	Polybutylene succinate adipate
PCL	Polycaprolactone
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxy butyric acid
PLA	Polylactide
PP	Polypropylene
PS	Polystyrene
PVA	Polyvinyl alcohol
PVC	Polyvinylchloride

Data availability

Data will be made available on request.

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